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Numerical Simulations of Dusty Colliding Wind Binaries

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This thesis is dedicated to my Mum, without her help these past 26 years, there's no way I would have written this.

I'll pay you back I promise!

Acknowledgements

Thanks everyone.

Abstract

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Abbreviations

CWB	Colliding Wind Binary	Section 2.1.1
GMC	Giant Molecular Cloud	Section 2.1.1
OB	O or B type star	Section 2.1.1
WC	WR Carbon Phase	Section 2.1.2
WCd	Dust forming WC star	Section 2.4.3
WCR	Wind Collision Region	Section 2.4.1
WN	WR Nitrogen Phase	Section 2.1.2
WO	WR Oxygen Phase	Section 2.1.2
WR	Wolf-Rayet	Section 2.1.2

Table 1: List of common abbreviations, if an abbreviation is important enough to warrant a subsection it is referenced

Common Symbols

η	Wind momentum ratio	
χ	Cooling parameter	
$\Lambda(T)$	Cooling function	
a	Grain radius	
z	Dust-to-gas mass ratio	
M_*	Stellar mass	
L_*	Stellar luminosity	
$\dot{M}$	Mass loss rate	
v_∞	Wind terminal velocity	
C	Courant-Friedrichs-Lewy condition	
τ_{KH}	Kelvin-Helmholtz timescale	Equation 2.1a
τ_{ff}	Free-fall timescale	Equation 2.1b

Table 2: List of common symbols, if symbol requires a derivation, the appropriate equation is referenced

$M_\odot$	Solar mass	1.988×10^{33} g
$M_\odot\,yr^{-1}$	Solar mass per year	6.301×10^{25} g s^{-1}
$L_\odot$	Solar Luminosity	3.828×10^{33} erg s^{-1}
AU	Astronomical Unit	1.496×10^{13} cm
pc	Parsec	3.086×10^{18} cm

Table 3: List of common units, with value in CGS units

Chapter 1

Introduction and Motivation

Chapter 2

Background

2.1 Early-Type Stars

The term Early-type stars is quite possibly the epitome of Astrophysical naming conventions, it's a very old term, coming from the dawn of astrophysics itself, quite opaque as to what it means, and also by definition *completely wrong*. In fact it is one of the most wrong pieces of terminology I can think of.[1] The first generation of astrophysicists found themselves asking very important questions such as "what even *are* stars" and "what possible mechanism can allow a star to burn for so long?" Each of these questions was rather pressing for the burgeoning field, and the scientific community was aching for an answer.

Of course, like all pressing questions of the 19$^{\text{th}}$ century, it fell to Lord Kelvin to provide a convincing but incorrect answer. Kelvin assumed that gravitational collapse was the mechanism for a stars long-term heating, with younger, "early" type stars shining the brightest. Not only was the mechanism incorrect, but typically older main sequence stars are more luminous than their younger counterparts of a similar mass! However, as is the case with astrophysical terminology, the term stuck, to the confusion of many young astrophysicists.

Instead, we now know that stars produce their energy through fusion, from the substellar deuterium and lithium burning, to the low-mass pp-chain & CNO hydrogen burning processes, and finally to the triple-α and more exotic fusion processes for evolved massive stars. The more massive the star the greater the internal pressure, leading to more difficult, but far more energetic fusion processes. This drastically increased energy output comes at the cost of a far shorter lifespan, as the rate of fuel consumption increases exponentially, while the available fuel has only increased a small amount [1].

2.1.1 OB-type stars

And with that we shift our gaze to high-mass stars, with the most massive of all being the O and B type stars, these are extremely luminous ($10^4 - 10^6\,\mathrm{L}_\odot$), and relatively short lived ($< 10^7$ Myr) stars. The age-old adage of a candle burning twice as bright

[1] Aside from astrophysicists calling something "warm", of course. That can quite literally mean anything from 10 to 10,000 Kelvin, depending on who you ask, what they're writing about, or how they're feeling at that particular moment. In fact, I'll probably end up falling into this same trap somewhere in this thesis as well!

lasting half as long applies to our studies of the cosmos, but it is more apt to compare a candle and a stick of dynamite when considering stars on each end of the Harvard classification system.

The formation of massive stars is a significantly less understood phenomena than their low-mass counterparts. In the low-mass case, a giant cloud collapses, radiating energy, which lowers the radius of thermostatic equilibrium for the cloud, this collapse time is referred to as the Kelvin-Helmholtz timescale, τ_{KH}. Another important timescale is the free-fall timescale, τ_{ff}, which is the time taken for a cloud to collapse.

$$\tau_{KH} \approx \frac{GM_*^2}{R_* L_*}, \tag{2.1a}$$

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\bar{\rho}}}, \tag{2.1b}$$

where M_* is the protostellar mass, R_* is the protostellar radius, L_* is the protostellar luminosity, and ρ is the mean density of the collapsing cloud.

Perhaps the most important distinction between massive star formation and its better understood counterpart is as a young protostar approaches the main sequence, the KH timescale is less than the free-fall timescale, meaning the material at the center of the collapsing cloud begins fusion while the bulk of core has collapsed onto the site of the future star. This burgeoning star begins to drive the weakly gravitationally coupled collapsing material away due to its sheer luminosity, driving this material outwards, causing it to accrete and shock material within the GMC.

Another important consideration is the role of angular momentum as the star collapses, the particularly massive cloud involved in massive star formation is more prone to fragmentation, meaning that massive stars typically form with an orbital partner, whilst approximately $2/3^{\text{rds}}$ of low-mass stars are part of a binary or multiple system, this value is near-total. As such, the environment within an OB association after star formation consists of numerous young stars in tightly-knit groups disrupting the entire region.[1]

Initially, the young massive star begins burning hydrogen, whilst lower mass stars utilise the p-p chain fusion reaction, the extremely high temperatures of a massive

[1] This is a bit like living in Headingley, Hyde Park, or any other area with lots of Undergraduates.

stellar core ($> 10^7$ K) ensure that the more energetic CNO cycle is more dominant:

$$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma \tag{2.2a}$$
$$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+} + \nu_e \tag{2.2b}$$
$$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma \tag{2.2c}$$
$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma \tag{2.2d}$$
$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e \tag{2.2e}$$
$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He \tag{2.2f}$$

[3]

2.1.2 Wolf-Rayet stars

As this young massive star evolves along the main sequence, burnable hydrogen becomes increasingly scarce, but as this star can sustain extremely high internal pressures and temperatures, it switches from hydrogen burning pp chain and CNO cycle to Helium burning with the triple-α process:

$$^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} \rightarrow ^{8}_{4}\mathrm{Be} \tag{2.3a}$$
$$^{8}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \rightarrow ^{12}_{6}\mathrm{C} + 2\gamma \tag{2.3b}$$

[2]

Star	$\dot{M}$ $M_{\odot}\,yr^{-1}$	v_{∞} $km\,s^{-1}$	Mechanism
Sun	10^{-14}	400	Thomson scattering
Red Giant	$10^{-7} - 10^{-9}$	30	Dust driven
Red Supergiant	$10^{-4} - 10^{-6}$	10	Dust driven
OB Star	$10^{-7} - 10^{-8}$	2500	Line driving
Wolf-Rayet	10^{-5}	1500	Line driving

Table 2.1: Comparison of winds from various types of star

2.2 Stellar Winds

2.2.1 Stellar winds in low mass stars

Thomson scattering wind driving

Dust driven winds

2.2.2 Stellar winds in high mass stars

2.2.3 The CAK formalism

2.3 Interstellar Dust

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Chapter 3

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Chapter 4

Paper 1

Chapter 5

Paper 2

Chapter 6

Final Notes and Conclusion

Appendix A

Astrophysical Shocks

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